

# LOUDSPEAKER NONLINEARITIES

CAUSES      PARAMETERS      SYMPTOMS

## $K_{ms}(x)$ STIFFNESS VERSUS DISPLACEMENT

Loudspeakers use a suspension system to center the coil in the gap and to generate a restoring force which moves the coil back to the rest position. Only at low amplitudes there is an almost linear relationship between displacement  $x$  and restoring force  $F$ . The restoring force may be described by the product  $F = K_{ms}(x)x$  of displacement  $x$  and stiffness  $K_{ms}(x)$  varying with displacement.

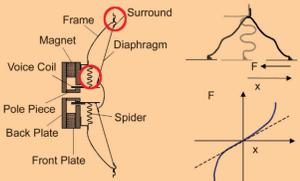


Figure 1: Suspension system in a conventional loudspeaker (sectional view) and the nonlinear force-deflection curve

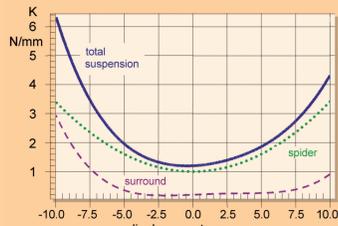


Figure 2: The total nonlinear stiffness  $K_{ms}(x)$  of the driver suspension measured dynamically by using an audio-like stimulus. The properties of the suspension parts are identified by performing a second measurement of the driver after removing 80% of the surround.

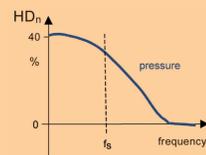


Figure 3: Nonlinear stiffness  $K_{ms}(x)$  generates high harmonic distortion at low frequencies where voice coil displacement is high.

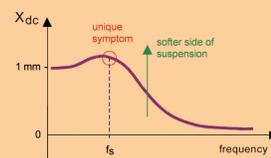


Figure 4: An asymmetric stiffness  $K_{ms}(x)$  of the suspension generates a dc-displacement dynamically.

### Symptoms

- ▶ high HD in sound pressure (for  $f < 2f_s$ )
- ▶  $X_{dc}$  moves coil to softer side of stiffness curve
- ▶ at resonance ( $f = f_s$ ):  $X_{dc}$  is dominated by  $K_{ms}(x)$
- ▶ low IMD in sound pressure
- ▶ low HD and IMD in current

## $Bl(x)$ FORCE FACTOR VERSUS DISPLACEMENT

The force factor  $Bl(x)$  describes the coupling between mechanical and electrical sides of an electro-dynamic transducer. It is the integral value of the flux density  $B$  over voice coil length  $L$ . The force factor  $Bl(x)$  is a function of voice coil displacement, depending on the geometry of the coil and the magnetic field generated by the magnet.

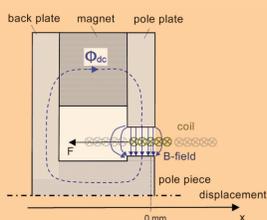


Figure 5: Voice coil current flowing in a static magnetic field generates an electro-dynamic force.

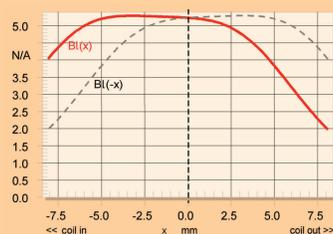


Figure 6: Force factor  $Bl(x)$  versus voice coil displacement  $x$ . The dashed curve represents the mirrored characteristic  $Bl(-x)$  to reveal the asymmetry of the nonlinearity.

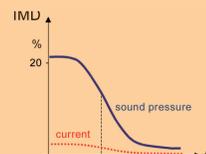


Figure 7: Characteristic frequency response of intermodulation distortion (IMD) in sound pressure output and input current caused by nonlinear force factor  $Bl(x)$  (using bass sweep technique with  $f_2 = 20f_s$ ). The IMD decreases above resonance frequency  $f_s$  because the bass tone at  $f_1$  produces less voice coil displacement.

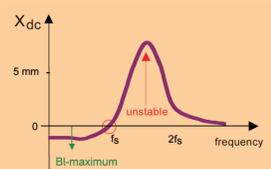


Figure 8: Typical response of dc-displacement  $X_{dc}$  versus frequency caused by a driver (in free air) with an asymmetric  $Bl$ -curve as shown in Figure 6

### Symptoms

- ▶ high HD in sound pressure ( $f < 2f_s$ )
- ▶ high IMD in sound pressure ( $f_1 < f_s, f_2 > f_s$ )
- ▶ direction of  $X_{dc}$  varies with frequency:
  - for  $f < f_s$ : small  $X_{dc}$  towards maximum of  $Bl$ -curve
  - for  $f = f_s$  (resonance): no dc-part generated ( $X_{dc} = 0$ )
  - for  $f > f_s$ :  $X_{dc}$  away from BL-maximum
  - for  $f \approx 1.5f_s$ : high values of  $X_{dc}$  ( $\rightarrow$  may become unstable)
- ▶ low distortion in current

## $L_e(x)$ INDUCTANCE VERSUS DISPLACEMENT

The current produces a magnetic ac-field which depends on the position of the coil. If the coil is in free air the magnetic flux is much lower than operating the coil in the gap where the surrounding iron path decreases the magnetic resistance. Current induced in the conductive material (shorting rings or caps made of aluminum or copper) as shown in Figure 9 generates a counter flux which reduces the total ac-flux significantly.

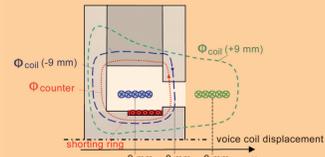


Figure 9: Magnetic ac-flux  $\Phi_{coil}$  generated by the voice coil current for positive and negative displacement  $x$  of the coil and the counter flux  $\Phi_{counter}$  generated by a shorting ring.



Figure 10: Placing the shorting ring below the gap reduces the voice coil inductance  $L_e(x, i = 0)$  at negative displacement and gives an almost constant inductance.

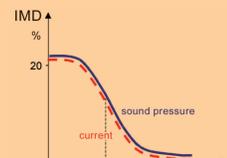


Figure 11: Inductance  $L_e(x)$  varied by displacement causes the same characteristic frequency response as intermodulation distortion (IMD) measured in sound pressure and current. Above resonance the bass tone  $f_1$  produces less displacement and the IMD decreases (bass sweep technique with  $f_2 = 20f_s$ ).

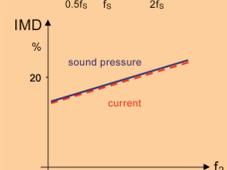


Figure 12:  $L_e(x)$  generates IMD which rises by  $\approx 6\text{dB/octave}$  with the frequency  $f_2$  of the voice tone (voice sweep technique with  $f_1 = 0.5f_s$ ).

### Symptoms

- ▶ moderate HD in sound pressure and current for  $1.5f_s < f < 4f_s$
- ▶ high IMD in sound pressure and current ( $f_1 < f_s, f_2 > 7f_s$ )
- ▶ small  $X_{dc}$  always towards the maximum of  $L_e(x)$
- ▶  $X_{dc}$  has a minimum at the resonance frequency  $f_s$

## $L_e(i)$ INDUCTANCE VERSUS CURRENT

Figure 13 illustrates the nonlinear relationship between magnetic field strength  $H$  and flux density (induction)  $B$  for three different voice coil currents. For  $i = 0$  the magnet produces the field strength  $H_2$  which determines the working point in the  $B(H)$ -characteristic. A high positive current ( $i = 10\text{A}$ ) increases the total field strength  $H_3$  and operates the iron at higher saturation where the permeability is decreased. The variation of the permeability  $\mu(i)$  causes a dependency of the inductance  $L_e(x, i)$  on current  $i$ .

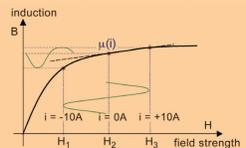


Figure 13: The nonlinear relationship between magnetic field strength  $H$  and flux density (induction)  $B$  in the iron material causes variation of the permeability  $\mu(i)$  versus voice coil current  $i$ .



Figure 14: Voice coil inductance  $L_e(i, x = 0)$  versus voice coil current  $i$  with and without shorting ring. Applying a shorting material also reduces „flux modulation“ because the magnitude of the total ac-flux  $\Phi_{ac}(i)$  is reduced.

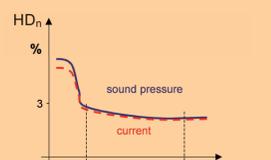


Figure 15: Current varying inductance  $L_e(i)$  generates harmonic distortion (HD) at higher frequencies which are equal in sound pressure and current. The displacement varying nonlinearities ( $Bl(x)$ ,  $K_{ms}(x)$  and  $L_e(x)$ ) can not produce significant harmonic distortion (HD, THD) at those frequencies because the displacement is small.

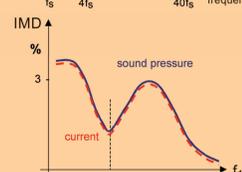


Figure 16: The current varying inductance  $L_e(i)$  generates identical intermodulation distortion (IMD) in sound pressure and current. There is also a characteristic dip at resonance frequency  $f_s$  where the current is low (using bass sweep technique with  $f_2 = 20f_s$ ).

### Symptoms

- ▶ moderate HD in sound pressure and current ( $f > 4f_s$ )
- ▶ moderate IMD in sound pressure and current ( $f_1 < 2f_s, f_2 > 7f_s$ )
- ▶ for  $f_1 = f_s$  IMD in sound pressure and current exhibits a minimum

### LARGE SIGNAL MODEL

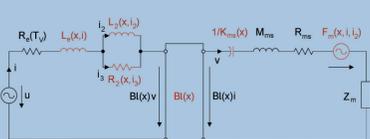


Figure 17: Electrical equivalent circuit of the electro-dynamic transducer. The dominant loudspeaker nonlinearities may be represented by lumped elements having varying parameters.

- Lumped parameters:**
- force factor  $Bl(x)$  of the electro-dynamical motor
  - stiffness  $K_{ms}(x)$  of the suspension
  - voice coil inductances  $L_e(x, i), L_2(x, i)$
  - resistance  $R_2(x, i)$  due to losses from eddy currents
  - dc-resistance  $R_e(T_v)$  of voice coil
  - impedance  $Z_m$  representing other mechanical and acoustical elements

- State variables:**
- displacement  $x$
  - velocity  $v$
  - current  $i$
  - voltage  $u$
  - reluctance force  $F_m(x, i, i_2)$
  - voice coil temperature  $T_v$

### EFFECT OF THE CURVE SHAPE

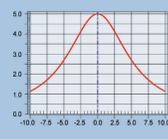


Figure 18: Symmetrical Nonlinearity

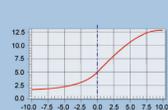


Figure 20: Asymmetrical Nonlinearity

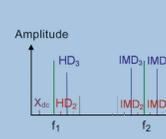


Figure 19: Symmetrical nonlinearity generates high 3<sup>rd</sup>-order distortion ( $HD_3, IMD_3$ ).

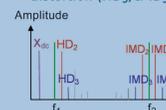


Figure 21: Asymmetrical nonlinearity generates high 2<sup>nd</sup>-order distortion ( $IMD_2, HD_2$ ).

### DISTORTION MEASUREMENT

using a two-tone stimulus ( $f_1 \ll f_2$ )

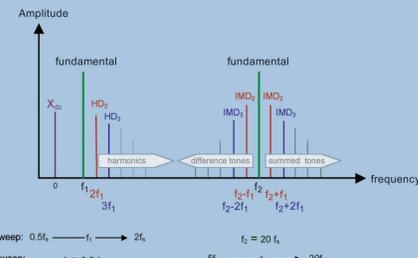


Figure 22: The intermodulation distortion is measured by varying the low frequency tone  $f_1$  (bass sweep technique) or varying the high-frequency tone  $f_2$  (voice sweep technique).

### OVERVIEW OF SYMPTOMS

such as harmonic distortion (HD), intermodulation distortion (IMD), amplitude modulation distortion (AMD), dc-displacement ( $X_{dc}$ ) generated by dominant loudspeaker nonlinearities.

Nonlinearities	SYMPTOMS GENERATED IN MONITORED STATE VARIABLE						
	Sound Pressure (bass sweep)	IMD (voice sweep)	HD (voice sweep)	AMD (voice sweep)	Current (bass sweep)	IMD (bass sweep)	Displacement ( <b>voice sweep</b> )
$K_{ms}(x)$	X						$X_{dc}$
suspension (spider + surround)							$X_{dc}$
$Bl(x)$ electro-dynamical motor	X	X	X	X			$X_{dc}$
position of coil in the gap	X	X	X	X	X*	X*	X
„flux modulation“	X	X	X	X			
Variation of Geometry of cone and suspension	X	X	X	X			
Young's modulus $E(t)$ of cone and suspension	X	X	X	X			
Flow resistance $R_e(t)$ in parts of vented enclosures	X						
Doppler Effect (radiation of sound waves)	X						
Wave Steepling (sound propagation at high SPL)	X						

\*provides unique symptoms which are sufficient for the identification of the nonlinearity.

### REFERENCE

- step-by-step instructions (KLIPPEL Application Notes):
- 01 Optimal Voice Coil Position
  - 02 Separating Spider and Surround
  - 03 Adjusting the Mechanical Suspension
  - 04 Measurement of Peak Displacement  $X_{max}$

- 05 Displacement Limits due to Driver Nonlinearities
- 06 Measurement of Amplitude Modulation
- 07 Measurement of Weighted Harmonic Distortion HI-2
- 08 3D Intermodulation Distortion Measurement
- 09 3D Harmonic Distortion Measurement
- 10 AM and FM Distortion in Speakers
- 11 Check for Dominant Flux Modulation

- 12 Causes for Amplitude Compression
- 13 Dynamic Generation of DC-Displacement
- 14 Motor Stability
- 15 Checking for Compliance Asymmetry
- 16 Multi-tone Distortion Measurement
- 17 Credibility of Nonlinear Parameter Measurement

- 18 Thermal Parameter Measurement
- 19 Air Convection Cooling of Loudspeakers
- 20 Measurement of Equivalent Input Distortion
- 21 Reduce Distortion by Shifting Voice Coil
- 22 Rub & Buzz Detection without Golden Unit
- 23 Rub & Buzz Detection with Golden Unit
- 24 Measuring Telecommunication Drivers